

The Origin of Cosmic Rays

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Abstract

It is generally regarded that the bulk of cosmic rays originate in the Galaxy and that those below the 'knee' (the rapid steepening in the energy spectrum) at a few PeV come from Galactic supernovae, the particles being accelerated by the shocks in the supernova remnants. At higher energies, there are problems in that conventional SNR - which surely constitute the bulk of the sources - have a natural limit at a few tens of PeV (for iron nuclei). The question of the origin of particles above this limit is thus an open one. Here we examine a number of possibilities: a variety of supernovae and hypernovae, pulsars, a Giant Galactic Halo and an Extragalactic origin.

A relevant property of any model is the extent to which it can provide the lack of significant irregularity of the energy spectrum, its intensity and shape together with structures such as the 'second knee' at the sub-EeV energy, in addition to the well known 'knee' and 'ankle'. Although it is appreciated that spectral measurements are subject to systematic as well as random errors we consider that contemporary data are good enough to allow at least some progress in this new field. These aspects are examined for particles of all energies and it is shown that they can constrain some parameters of the proposed models.

In the search for origin above PeV energies we conclude that shocks in the Galactic Halo, whatever their source (Galactic wind, relativistic plasmoids - 'cannonballs', multiple shocks from supernovae etc.) are most likely, pulsars such as B0656+14 and hypernovae come a close second although such a suggestion is not without its difficulties. What is most important is that *trapping of particles in the Halo is needed to reduce irregularities of the energy spectra both below and above the 'knee' caused by the stochastic nature of supernova explosions and other potential (discrete) Galactic sources.*

We argue that precise experimental studies of spectral 'irregularities' will provide considerable help in the search for cosmic ray origin.

1 Introduction

Some ninety years after the discovery of the cosmic radiation (CR) there is still dispute about its origin, at least for energies above the 'knee' in the spectrum. Indeed, it has

often been said that 'had such particles not been observed they would never have been predicted'.

As with other high energy bands in the CR spectrum, the problem is not with the total energy content but rather with achieving single particle energies of the required magnitude.

Below the knee at 3 PeV there is general agreement that supernova remnants (SNR) are responsible and much work has been done [1, 2]. We, ourselves, have published a number of papers (*eg* [3, 4]) and, most particularly [5, 6], in which we have made extensive Monte Carlo calculations for SN distributed at random in the Galaxy and determined the expected spectral shape. A satisfactory model has resulted, for energies below about 10 PeV, a characteristic feature being the presence of fine structure, viz. 'peaks' in the spectrum at about 3 and 12 PeV (when the spectrum is plotted as $E^3 I(E)$) due, in our initial concept, to oxygen and iron nuclei (helium and oxygen not being excluded, however) accelerated by a single, recent and nearby SNR. Very recent developments [7, 8] have lent support to this model.

In what follows, we examine the source of CR at higher energies in some detail. In fact, for some of the analysis, the proposed mechanisms for high energy particles impinge on the lower energies and it is necessary to examine the lower energy region as well. Particularly important is the relevance of the observed curvature in the spectrum of atomic nuclei to the model of shock acceleration and the fluctuations in spectral shape (see the Appendix). Potential sources for post-PeV particles are various supernovae and hypernovae, pulsars, Galactic Halo shocks, acceleration in the magnified magnetic fields of young supernova remnants (SNR), re-acceleration by collective effects of multiple SNR shocks and Extragalactic (EG) phenomena. We endeavour to rank these possibilities in decreasing order of likelihood.

2 Phenomenology of Cosmic Rays above PeV energies

At the knee at ~ 3 PeV the cosmic ray energy spectrum suddenly steepens and continues to fall with a slope index of about 3.0 up to ~ 400 PeV. It is commonly assumed that the knee is the only feature in the energy spectrum until the 'ankle' is reached, at an

energy approaching 1000PeV. It is, however, in our view, highly likely that there is more ‘structure’ in the spectral shape; every physical phenomena in the Galaxy is spatially (and temporally) variable i.e., is irregular and there is no reason why the CR spectrum should not have irregularities. In most - and perhaps all - models of the knee there should be fine structure at some level in the general power law, due to cut-offs in the spectra of constituent CR nuclei. Indeed, we have claimed to have found a small second peak in the all-particle spectrum at about 12 PeV [9]. If the dominant element at the knee is oxygen, then the position of the second peak can be an indicator that it is due to the cut-off of the iron group. Since the abundance of trans-iron elements is small, CR above ~ 20 PeV should have another origin although there is a model in which trans-iron elements can make a substantial contribution to the total CR intensity after the cut-off of iron [10]; a model to which we do not subscribe.

There is another interpretation for the structure of the spectrum at and above the knee: that rather than oxygen, it is, instead, helium which is dominant at the knee, and the second peak is attributed to oxygen (or in general to the CNO group) rather than iron. In this case, if the iron is still abundant in CR, one can expect the existence of a third peak in the spectrum at ~ 40 PeV caused by the cut-off of iron, assuming that all cut-offs occur at the same rigidity. The experimental indications of the existence of a third peak are gradually accumulating, but the general situation is still controversial [11, 12]. Hopes of clarifying the situation are connected with the expected results from KASCADE-Grande [13].

The positions of the second and third peaks are practically independent of the model of the knee. In two alternatives, in which cut-offs of the individual elements occur at a fixed rigidity or at a fixed energy per nucleon, the position of the cut-off energy in the energy spectrum is proportional either to the charge Z or to the mass A of the individual element. In both cases the interval between the cut-off energy for He and Fe is practically the same (in logarithmic units).

Independently of the visibility of the third peak it is evident from the experimental data that above 40 PeV ($\log E, GeV = 7.6$) we have a wide energy interval in which the CR energy spectrum extends as a power law with an approximately constant differential slope index of $\gamma \simeq 3.04$ up to $\log E, GeV = 8.6-8.9$. At this energy the CR spectrum has another

faint feature known as 'the second knee', which is a further steepening with $\gamma \simeq 3.18$ up to an energy of the 'ankle' at $\log E \approx 9.5 - 10.0$. Berezhinsky et al. [14, 15] consider that soon after the third 'iron' peak extragalactic protons enter the scene and the second knee arises from them with the rise of their energy loss for the production of electron-positron pairs in electromagnetic interactions with the cosmic microwave background (CMB) causing the ankle. In this case the good tuning of Galactic switch-off and Extragalactic switch-on energies in the region of $\log E = 8 - 9$ is puzzling.

On the contrary, Wibig and Wolfendale [16] argue that Galactic CR extend further after $\log E = 7.6$ up to the ankle, but they do not consider the origin of these Galactic CR, which should certainly change after the termination of iron from conventional supernovae. The hypothetical contribution of trans-iron elements [10] cannot completely fill the gap between the iron peak and the ankle. Here we shall try to analyze the situation at higher energies, largely in the PeV-EeV interval between the knee and the ankle, starting with supernovae and hypernovae, sources which have relevance both above and below the knee.

3 Analysis of the different models of CR origin above the knee

3.1 A variety of supernovae and hypernovae

To our knowledge, it was P.L.Biermann who suggested that another kind of supernova, coming from more massive and hot stars, such as Wolf-Rayet stars, might be responsible for the production of CR with energies above the knee [17]. This idea has been developed by Sveshnikova [18], who used the evidence that there are different classes of SN and even within a single class there is a spread of explosion energies. There is also a weak dependence of the maximum energy of accelerated particles E_{max} on the explosion energy within a single class but the difference between E_{max} for different classes of SN might be higher. The author integrated the spectra of accelerated CR with assumed distributions of explosion energies and showed that with certain fractions of different SN classes, taken mainly from observations, and certain assumptions about E_{max} for different classes, it is possible to reproduce the shape of the CR spectrum above the knee. As would be expected, the dominant contribution to the spectrum comes from the most energetic

classes: SNIbc and SNIIn.

We have made calculations for a number of scenarios, starting with the ‘standard SN’, viz SN energy of 10^{51} ergs, of which 10% goes into CR and a differential energy spectrum of the form $E^{-2.15}$. Full details of the diffusion characteristics, stochastic distribution of SN in the Galaxy, etc., are given in [18]. We refer to the particles as ‘protons’ but the results will refer to nuclei of the same rigidity of another element, with a suitable change in ordinate to represent the abundance of that nucleus. The Figures show our estimate of the energy spectrum of the proton component. In Figure 1a we show how the stochastic distribution of SN modifies the shape of the CR energy spectrum for just a single class of SN. The Figure shows 50 spectra produced by standard SN with $\log E_{51}=0$ and $\log E_{max}=5.6$ distributed randomly in space and time in the Galactic Disk. Here E_{51} is the explosion energy in 10^{51} erg units. Figure 1b shows the mean of these spectra and their standard deviation (we refer to the standard deviation of the logarithm of the intensity at a particular energy as the ‘irregularity’ at that energy [5, 19]). In the real Galaxy, grouping of SN in both space and time would cause the spread in spectra to be even bigger. Moving to Figures 1c and 1d, these show 50 spectra and their mean, respectively, for the case where $\log E_{51}$ has a log-normal distribution around $\log E_{51}=0$ with a standard deviation of $\sigma_{\log E_{51}}=1.2$. E_{max} has been taken dependent of the explosion energy as $E_{max} \propto \sqrt{E_{51}}$ [18]. It is seen that the spread of explosion energies leads to

- a displacement of the knee energy from $\log E_{max}=5.6$ up to 7-8 and makes the knee smoother
- an increase of the CR intensity by up to an order of magnitude
- an increase in the degree of irregularity of the spectrum.

The first two items are a consequence of the distribution of E_{51} which is made on a log-normal scale while the CR intensity is $\propto E_{51}$. The rise of the irregularity is a consequence of the introduction of the big explosion energies which increase the fluctuations. Evidently a smaller value of $\sigma_{\log E_{51}}$ than adopted would give consistency between predicted and ‘*obs(P)*’, but only at sub-PeV energies.

Figure 2 shows the CR spectra produced by the two main types of SN which are thought to contribute to the bulk of CR: SNIbc and SNIIn [18]. The explosion energy

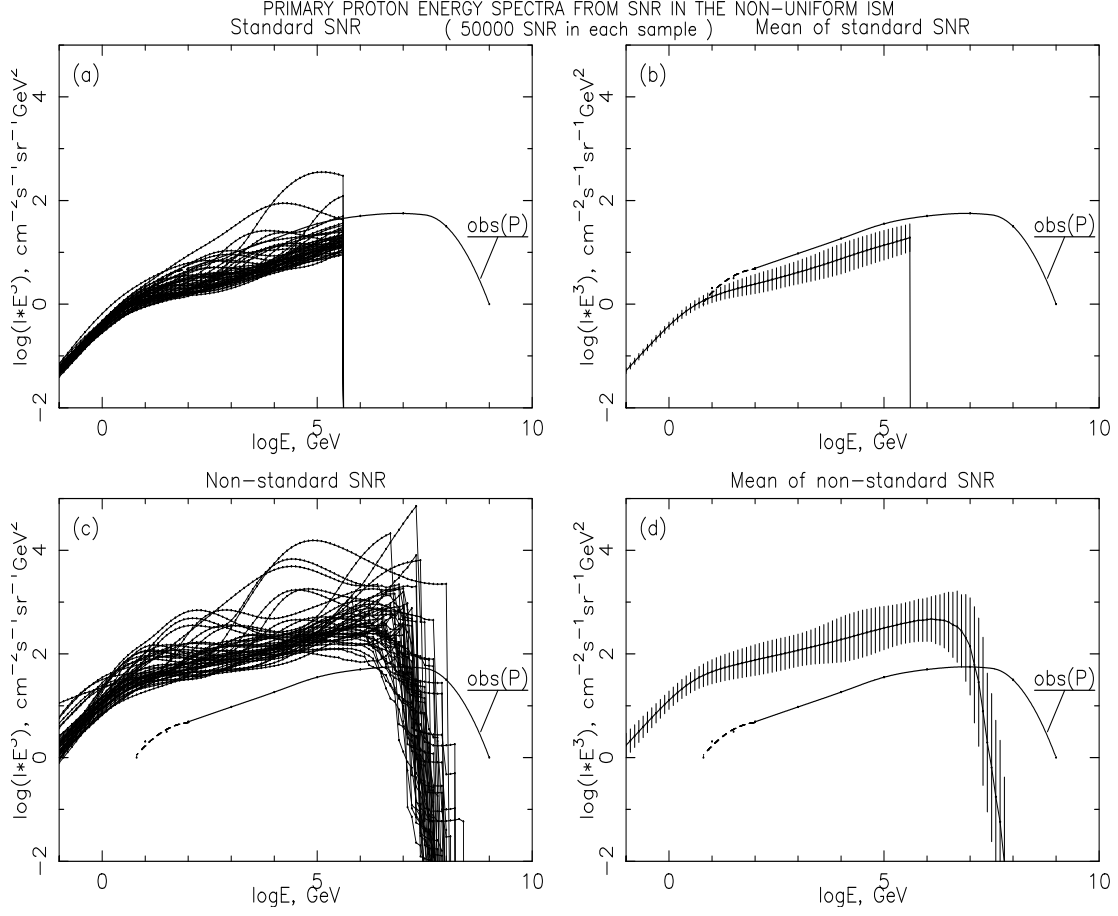


Figure 1: Energy spectra of CR accelerated by SN (50 samples with 50000 SN in each): (a) with a standard explosion energy $\log E_{51}=0$ and a maximum particle energy $\log E_{max}=5.6$; (b) the mean spectrum and its irregularity for samples shown in (a) - the irregularity is the standard deviation from the mean CR intensity for different samples of the spectrum indicated by vertical lines; (c) with a log-normal distribution of an explosion energy around $\log E_{51}=0$ with a standard deviation of $\sigma_{\log E_{51}}=1.2$ and $E_{max} \propto \sqrt{E_{51}}$; (d) the mean spectrum and its irregularity for the samples shown in (c). The curve $obs(P)$ is our estimate of the proton spectrum (or the rigidity spectrum for heavier nuclei) needed to fit the experimental data [20]. ‘ E_{51} ’ is the explosion energy in units of 10^{51} erg

of both SN is the same as in Figure 1 *ie* distributed around $\log E_{51}=0$ with $\sigma_{\log E_{51}}=1.2$. E_{max} of SNIbc is also the same, *ie* $\propto \sqrt{E_{51}}$, and distributed around $\log E_{max}=5.6$. E_{max} of SNIIn, due to the different progenitors and the environment, is 15 times higher and distributed around $\log E_{max}=6.8$. The fraction of SNIbc among all SN is 0.2, that of SNIIn is 0.1 [18]. Figures 2a and 2b show 50 samples of the total spectra produced by both SNIbc + SNIIn and their mean respectively. Figures 2c and 2d show the contribution of only SNIIn and their mean.

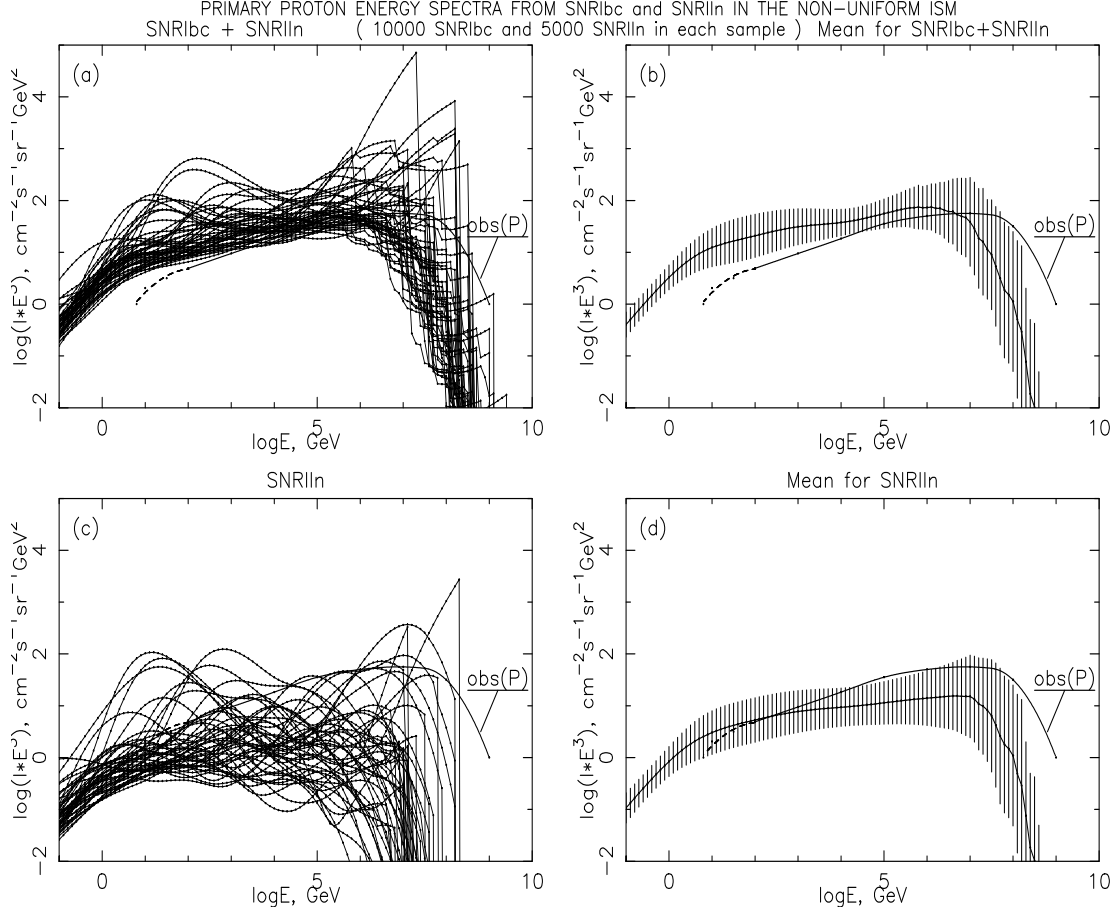


Figure 2: Energy spectra of CR accelerated by two types of SN - SNlbc and SNlIn (50 samples with the same distribution of $\log E_{51}$ for both, but different distributions of $\log E_{max}$ (see text)): (a) the summed spectra of 10000 SNlbc and 5000 SNlIn; (b) the mean spectrum and its irregularity for samples shown in (a); (c) the contribution to the total spectrum of only SNlIn; (d) the mean spectrum and its irregularity for SNlIn samples shown in (c). As in Figure 1 the irregularity in Figures 2b and 2d is the standard deviation from the mean CR intensity for different samples of the spectrum indicated by vertical lines. The curve $obs(P)$ is as in Figure 1.

It is seen that

- the total CR intensity decreases by a factor of 3 compared with Figure 1c and 1d due to the decreased SN rate (30%)
- the irregularity of the spectra increases because of the presence of the rarer type of SN - SNlIn
- the maximum energy increases by about an order of magnitude

- the sharpness of the knee decreases due to the increase of E_{max} (although it could, of course, be restored by involving the presence of a close and recent SN).

Figure 2 demonstrates that CR beyond the knee cannot be produced just by the adopted fractions of SN with a higher E_{max} . The distribution of the explosion energy and the maximum particle energy combined with a reduced rate of explosions give rise to an extreme irregularity of the expected spectra, which is in fact not observed and there is still a high energy gap to be filled. The remedy could lie in an occasional even stronger source; this 'stronger source' may be a yet more effective SNR using the model of Bell [21]. Here, SNR expanding into dense molecular clouds, compress the magnetic fields and rapidly accelerate particles to very high energies. We call these SNR, BSNR. The ensuing spectra would be even more variable, however. A Giant Galactic Halo which traps the particles is another possibility; such a Halo could smooth out the BSNR fluctuations and it may, or may not, provide further acceleration.

A mixed mass composition in the *energy* spectra can reduce the irregularity of the spectra, since it displaces the same rigidity spectra for different nuclei with respect to each other when plotted in terms of energy, and the excursions in intensity cease to be completely in phase. However, this effect is small below the rigidity cutoff and only makes the cutoff in the energy spectrum less sharp compared with the cutoff in the rigidity spectrum (see Appendix).

3.2 Pulsars

3.2.1 General Remarks

In a recent paper [22] we made the case for pulsars being serious candidates for the origin of particles beyond the knee. Some general remarks are necessary first. When a different type of source is postulated for energies above the knee, the (comparatively) smooth join of the two spectra is a worry. In the case of pulsars, the near equality of the total kinetic energy carried by an SNR and the average initial rotation energy of a pulsar means that the join might be expected to be not too traumatic.

3.2.2 The CR Energy Spectrum from B0656+14

In [6, 23] we claimed that the SNR Monogem Ring is a good candidate for such a Single Source. It has been shown that the pulsar B0656+14, which is close to the morphological center of the Monogem Ring, is associated with this SNR and this is a potential further source of CR. The rotation period P of this pulsar is 0.3848 sec, the spin-down rate \dot{P} is $5.5032 \cdot 10^{-14}$. In the rotating dipole model these parameters correspond to a very narrow peaked emission of cosmic rays at a rigidity of 0.25 PV [22], a rigidity remarkably close to the knee. This rigidity corresponds to a knee energy of about 3 PeV for nuclei as heavy as Mg where it would give a very narrow peak of its energy spectrum, and cannot be invoked in its simple form. However, the pulsar could contribute to energies above the knee if cosmic rays emitted by it in the past were confined within the SNR for a long time after its explosion and released not long ago. If the pulsar emits predominantly iron nuclei they can contribute to the cosmic ray energy spectrum up to well above the knee.

Figure 3 shows the results of our calculations for MONOGEM [22] assuming the emission of just protons and iron nuclei and choosing an appropriate trapping time. The propagation parameters were our usual ones [5]. Admittedly the model is rather ad hoc but it is physically attractive. However, the energetics are demanding. ‘P’ requires that most of the rate of loss of rotational energy of the pulsar goes into protons, a more reasonable fraction (3%) is needed for iron nuclei. A rather serious problem concerns the expected anisotropy if most of the CR came from a single local pulsar.

3.2.3 High Energy CR From Many Pulsars

A more likely scenario is that a number of pulsars contribute perhaps most of the CR flux above the knee. This model has its adherents. In one such model [24] a distribution of pulsar periods at birth is chosen - which is not unreasonable - and iron nuclei are involved such as to give the measured CR spectrum. The energetics are reasonable. The anisotropy problem is reduced by postulating a Giant Halo (20-50 kpc radius), as is required in our own analysis.

The problem encountered by all the pulsar models is the need for young pulsars, with periods as low as a few ms; the presence of such young pulsars in sufficient numbers is subject to debate but progress is being made.

We conclude that pulsars can be considered as contenders for the origin of CR above the knee if coupled with a Giant Halo.

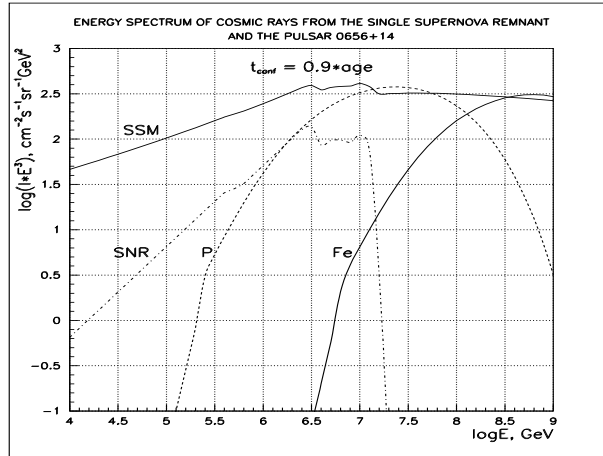


Figure 3: Energy spectra of CR from the pulsar B0656+14, observed at the Earth. They are calculated for a confinement time t_{conf} , during which cosmic rays were confined within the SNR shell, lasting 0.9 times the pulsar age. The CR nuclei emitted by the pulsar are protons (P , dashed line) and iron-nuclei (Fe , full line), the efficiency of proton acceleration is near unity and that for iron acceleration is taken as 0.03. The CR energy spectrum in the Single Source Model (which fits observations) is shown by the full line denoted as 'SSM' with the contribution of the SNR shown by the dash-dotted line denoted as 'SNR'

Such a scenario has a number of attractive features. The first is that the mass composition above 40 PeV continues to be heavy due to the dominance of iron nuclei stripped from the pulsar surface up to a second knee at ~ 400 PeV. The second is that the shape of the energy spectrum is close to the observed one. Very young and very rapidly spinning pulsars may have contributed to the 'gap' in Figures 1 and 2 (i.e. the range $\log E$: 8-10) by way of their particles being trapped in the Galactic Halo.

3.2.4 Fine structure in the region of 100 PeV

A topic which has relevance to CR production by pulsars, particularly, because of the likelihood of a near monogetic beam being generated by a pulsar of a particular age is the presence of 'fine structure' in the primary spectrum. Consequently, we have searched for fine structure in the observed extensive air shower (EAS) size spectra in the region beyond the knee up to 1 EeV (1000 PeV) by the same running mean method as we did in [25]. In order to enlarge the statistics of the data in the energy region above 100 PeV we added to the 40 EAS size spectra presented in earlier work 6 recent size spectra from the

GRAPES III EAS array [26]. The mean excess of the running means is shown in Figure 4 together with that derived from recent MSU results on EAS muon size spectra [27]. The small excess at $\log(N_{e,\mu}/N_{e,\mu}^{knee}) = 0.5$ corresponds to our second peak in the primary

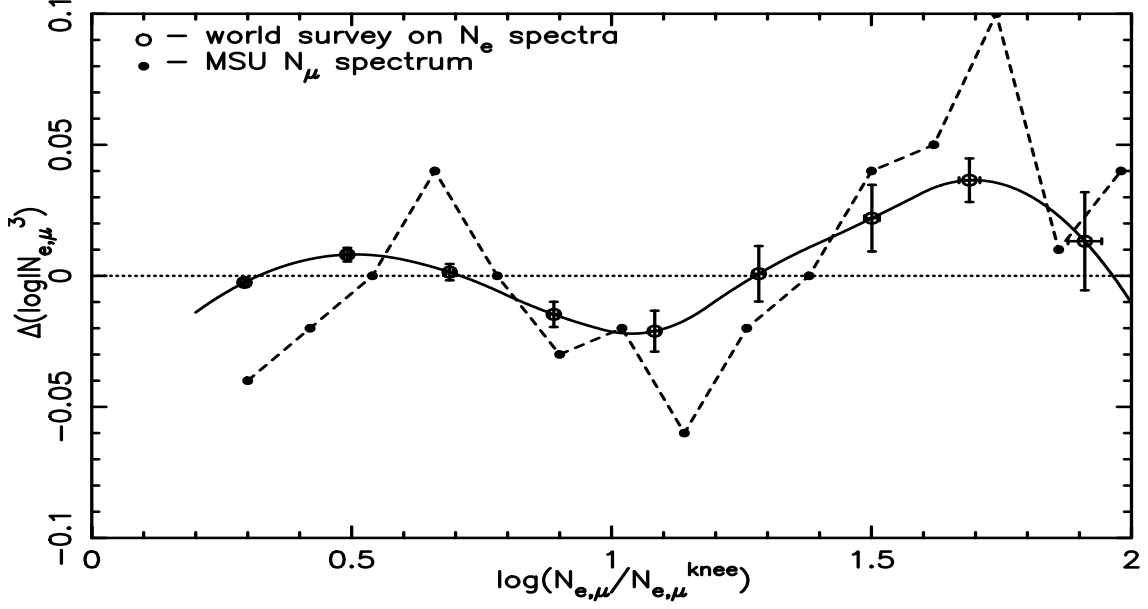


Figure 4: The mean excess over the running means for the 46 EAS size spectra (full line) and the MSU muon size spectrum [27] (dashed line).

energy spectrum at about 12 PeV. Here $N_{e,\mu}$ are total numbers of electrons or muons in the EAS and $N_{e,\mu}^{knee}$ are corresponding numbers at the knee. We associated the second peak with the cutoff of iron nuclei accelerated by the Single Source SNR. However, in the region of $\log(N_{e,\mu}/N_{e,\mu}^{knee}) = 1.3 - 2$ there is another positive excess of running means with evidence for a positive curvature of the spectrum at about 100 PeV. The magnitude of the excess at ~ 100 GeV is significant in the EAS data ($\sim 4\sigma$) and the significance is increased still further by the peak at the same energy in the muon data. The shape of the iron spectrum from the pulsar B0656+14 shown in Figure 3 has a similar positive curvature in the 100 GeV energy region, although it is less sharp. It should be noted that the 'peak' at ~ 100 PeV is at a higher energy than the 40 PeV we would expect if the knee were due to helium rather than oxygen and the relevant CR were accelerated by SNR.

The third advantage of the pulsar scenario is that the dominance of just a single pulsar above the second (iron) peak of the SSM gives a smooth spectrum with a small

irregularity beyond the knee which is the feature actually observed. It can be remarked that the rigidity of iron nuclei at $\log E = 8.5$ is probably still too low for directional anisotropies associated with this nearby SNR (Monogem) to be detected (see §3.2.6).

3.2.5 The Confinement of CR Generated by Pulsars inside SNR

In the case of pulsar acceleration of CR there is the need for slow release of the particles. This is where the associated SNR should have relevance. The interaction between a pulsar and its surrounding nebula has been examined in many publications (see [28] and references therein). In [28] the confinement of particles generated by the pulsar inside the nebula is limited by the time taken for its diffusion radius to reach the shell created by the SN shock wave. In the framework of our model of the SN explosion [25] this time T_c is determined by the equation:

$$L(\frac{T_c}{\tau(E) + L/c})^{1/\alpha} = R_0(\frac{T_c}{T_0})^\beta \quad (1)$$

where the left hand side is for the diffusion radius and the right hand side is for the radius of the shock wave. Here L is the characteristic distance reached by the particles of energy E in the process of diffusion during their lifetime τ and c is the speed of light, R_0 , T_0 are parameters which determine the speed of the SNR radial shell expansion. We introduce the term L/c to limit the speed of diffusion to the speed of light, which is important at energies approaching 0.1 EeV. α is the coefficient which determines the character of the diffusion: $\alpha = 2$ for regular, 'gaussian', diffusion in a uniform interstellar medium, and $\alpha = 1$ for anomalous diffusion in a non-uniform turbulent medium with a Kraichnan-like spectrum of turbulence [29, 30]. On the right hand side of equation (1) we have the radius of the SNR shell as a function of time represented by $R(t) = R_0(\frac{t}{T_0})^\beta$ with $R_0 = 50pc$, $T_0 = 2 \cdot 10^4$ years and $\beta = 0.5$. If we want this equation to be fulfilled for our standard confinement time, $T_c = 8 \cdot 10^4$ years, during which the radius of the shell created by the shock wave reaches 100 pc, we have to assume that the ordinary diffusion coefficient ($\alpha = 2$) for the ~ 100 PeV particles which we should like to confine inside the shell, is $D \approx 2 \cdot 10^{28} cm^2 s^{-1}$. It is much less than the $\sim 2 \cdot 10^{31} cm^2 s^{-1}$ adopted by us for anomalous diffusion outside the shell. An equivalent mechanism is to assume that the SNR shell is not transparent to the particles until the remnant 'bursts' (see later).

All these estimates are very approximate and given just for an illustration of the conclusion that the diffusion of particles generated by the pulsar inside the SN shell has to be much slower than in the ISM outside the shell. Some support comes from the HESS observation of the relatively young (a few thousand years) SNR G0.9+0.1 near the Galactic Center [31]. They could not see the extension of the source and concluded that *the gamma-ray emission appears to originate in the plerionic core of the remnant, rather than the shell*. It could mean that CR accelerated by the pulsar diffuse so slowly that even after a few thousand years they have not reached the shell.

When, after a long time, the diffusion front of CR approaches the SN shell, the CR particles do not necessarily escape. In our case of particles emitted by a pulsar they catch up a receding shell from behind, i.e. from its downstream region. They lose a part of their energy accelerating and modifying the shock wave and appear with a smaller energy within the shock. The loss of energy is even larger if the particles are reflected back from the shock by a receding magnetic mirror. Calculations show that the probability of such reflection is quite high [32]. Thus, the scenario looks as if for the ambient and upstream CR particles the shock wave and expanding SNR shell serve as an accelerator while for downstream CR they serve as a trap.

If there is a supersonic particle wind from the pulsar, driven by its rotation, then one can expect the existence of a termination shock where its speed decreases enough to become subsonic and particles accelerated by the pulsar can be trapped inside the smaller volume of the pulsar wind ‘nebula’ limited by the termination shock and their confinement time can be even longer than for trapping in the associated SNR.

3.2.6 The Anisotropy

The dominance of a Single Source such as the Monogem Ring SNR and its associated PSR B0656+14 in the knee region and beyond can create problems with the anisotropy of CR. However, there are a few indications that the expected anisotropy does, in fact, exist. The global search for an anisotropy, made in [33, 34], has shown that at primary energies $10^{16} - 10^{17}$ eV there is an excess of the CR intensity in the general direction of the Monogem Ring. More recent studies at lower energies [35, 36] have also indicated regions of excess intensity within the Monogem Ring, though at a low confidence level.

Therefore, we cannot exclude the possibility that this region of the sky gives an enhanced intensity of CR in a wide energy interval from sub-PeV up to tens of PeV energies.

3.3 A Giant Galactic Halo

3.3.1 General Remarks

If CR in the PeV - EeV energy range are of Galactic origin, with very energetic SNR and young pulsars as sources of their energy, then there needs to be a mechanism which reduces the irregularity of their 'explosions' and the effect of the short time when these sources are able to produce particles of the highest energy. The most natural way is to introduce a long term accumulation of CR within a confinement volume, similar to the well known 'leaky box' for the Galaxy, but with a much larger size and a longer lifetime in it. Such accumulation can be achieved with the help of a Giant Galactic Halo, a proposal that is not new but has important implications [37, 38, 39].

In conventional models of CR origin and propagation it is assumed that there is free escape from the Galactic Disk (with a typical scale height of ~ 1 kpc) into a Halo with, perhaps, a scale height of ~ 10 kpc. In fact, however, it seems likely that there is a Giant Halo, extending to perhaps 100kpc (or even further) from the Galactic Plane, in which there is plasma. Some evidence has come from gas displacements in the Magellanic Clouds which are interpreted as being due to the ram-pressure effect of Galactic gas rotating with the Galaxy [40]. Similar arguments favoring the existence of big halos for galaxies and even for clusters of galaxies have been put forward also in [41, 42, 43]. In [30] we showed that anomalous diffusion can help to create such a Giant Halo with a long tail of CR above and below the Galactic Disk.

A Halo, involving only diffusion, would not have a trapping effect as such, however. CR would simply diffuse out of the Disk due to the CR density gradient and not be accumulated. One has to introduce a 'membrane' or 'reflector' to stop further leakage, to reflect the outflow and to start the accumulation. It is here where the Galactic wind can help. Such a wind is to some extent similar to the Solar wind. It is due to the gas and CR pressure gradient in the Disk, its starting speed is supersonic and it itself may well accelerate particles in the Halo if the Mach number is high enough. Eventually, this wind loses its energy due to friction with the ambient gas in the Intergalactic Medium (IGM)

and at some distance from the Disk its speed becomes subsonic. This is the region where the 'termination shock' is formed. This termination shock can act to reflect and trap CR particles and perhaps accelerate them [39, 44, 45].

Table 1 shows characteristics of a possible Giant Halo with (near-)reflecting walls, largely using results derived by us from the data given in [39]. The figures given allow the energetics of the phenomenon to be put in perspective. The next subsection provides more details.

It must be said that there is no direct experimental evidence that the Galactic wind and its termination shock exist. They have been proposed as an analogy of the solar wind, which is detected by various spacecrafts and where there are indications from the Voyager I mission that the spacecraft is approaching the termination shock region in the heliosphere [46]. However, the assumption about the Galactic wind and the termination shock helps to fill the gap between the Galactic CR at 40-50 PeV and EG CR which may appear beyond the 'ankle' at a 3-8 EeV [16]. There is an alternative model, however, in which this interval is filled by the true EG CR and the transition occurs at a lower energy [14]. The assumption also helps us to understand a number of observed CR phenomena viz.

- the small radial gradient of CR intensity [47]
- the small irregularity of the CR energy spectrum (quantified in the Appendix)
- the small anisotropy of arrival directions.

The main aspects of the Giant Galactic Halo will be considered below. We discuss Halo acceleration, diffusion and simple trapping.

3.3.2 Halo Acceleration

In §3.1 we showed that the admission of a variety of explosion energies as well as a variety of SN types with some of them having much higher maximum energies E_{max} for the acceleration ('hypernova') allowed one to get CR particles above PeV energies (although, in its considered form, the maximum energy was still not high enough and BSNR and/or young pulsars were needed). However, the paucity of such sources and the high speed of the diffusion results in a very big irregularity of CR energy spectra in

this region. Even if one restricts the speed of the diffusion to the speed of light, as one must (formula 1) it does not reduce the irregularity very much (Figure 1). Therefore, we give preference to a more regular mechanism where high energy particles appear as the result of re-acceleration of lower energy CR particles emitted by the Disk by the shock waves in the Halo. The energy spectrum of these particles should be less irregular since the re-acceleration process seizes a large space in the Halo and integrates the spatial irregularities [39] arising in the Disk; specifically, estimates indicate that the anisotropies should be limited to a few percent (see the Appendix) and the corresponding distortion of the spectral shape should be small. For the re-acceleration another source of energy supply has to be invoked in addition to the 'direct' CR energy from SN explosions (*eg.* Galactic wind, rotation of the Galaxy, the remaining non CR - SNR energy, etc.)

In what appears to have been the first attempt at making calculations for acceleration in the Halo and at the termination shock [44, 45] attention was devoted to detailed calculations of the maximum energy achievable. The authors point out that the important acceleration time in a medium where the shock velocity is V_{sh} and the diffusion coefficient is D is $t_{acc} = 4D/V_{sh}^2$. Typical shock velocities of $\sim 500 km s^{-1}$ are invoked and the result is that, for a derived magnetic field of $\sim 0.07 \mu G$ at the termination shock at a radius of 100 kpc, protons can be accelerated to $\sim 6 \cdot 10^{18} eV$ (i.e a rigidity of $6 \cdot 10^{18} V$). The diffusion coefficient adopted is presumably $7.5 \cdot 10^{33} cm^2 s^{-1}$. We ourselves prefer a reversal length of $\sim 10 kpc$ [20], i.e. $D \simeq 3 \cdot 10^{32} cm^2 s^{-1}$, for which the maximum rigidity would be lower: $3 \cdot 10^{17} V$, i.e. approaching $10^{19} eV$ for iron; such an energy is adequate for Galactic CR.

Reverting to the earlier model it is interesting to note that the field compares well with our $0.1 \mu G$ averaged over the Halo and derived from an estimate of gas temperature ($\sim 10^6 K$) and density ($10^{-3} cm^{-3}$) [20]. Specifically, the shocked Halo will have a field of $\sim 0.1 \mu G$ at a radial distance of 1/3 of the termination shock radius.

If for the moment we ignore the need for an additional source of energy for the re-acceleration and take the CR injection from the Disk into the Halo as the only source of energy, its luminosity is about $5 \cdot 10^{40} erg \cdot s^{-1}$ from our model of a SN explosion [25]. With a radius to the termination shock of 100 kpc and an accumulation time of $10^{10} y$ (the age of the Galaxy) the corresponding energy density in the Halo is about $0.1 eV cm^{-3}$.

The energy density of *observed* CR with energy above 40 PeV is about $4 \cdot 10^{-6} \text{eV cm}^{-3}$. Therefore, if we associate CR above 40 PeV with CR from the Halo they should contribute also below 40 PeV, even for the case of the minimum energy supply. The spectrum of Halo CR at lower energies should be flatter than that with $\gamma = 3$ so as not to contradict observations (a retarding effect of the Galactic wind is postulated. In this case, the Galactic sources would be spasmodic, with no nearby ones at the moment).

In the SSM we composed the CR energy spectrum from two components: the spectrum of the Single Source and a so called 'background', the source of which we did not specify, but argued that it was created by the bulk of older and remote SNR, at least at energies below the knee. If we calculate the energy density created by this background we find that the minimum value of 0.1eV cm^{-3} corresponds to CR above $\sim 10^2 \text{GeV}$, which could be the 'low energy' cutoff for CR reaccelerated in the Halo. The real spectrum of CR particles in the Halo should extend to lower energies than $\sim 10^2 \text{GeV}$, particularly if an additional source of energy is invoked in the Halo.

Turning to the irregularities, due to the integration of individual spectra from different SN over the long accumulation time and large volume, the irregularities created by the stochastic nature of SN explosions will be smoothed and the resulting irregularity of the CR energy spectrum in the Halo should be close to zero. We shall demonstrate this fact later in §4 and the Appendix.

A more recent and more comprehensive model with acceleration at the termination shock has been given in [39]. The salient points are given in Table 1. Prominent features are that it is the pre-existing Galactic CR that are accelerated in the Halo, and few of the post-1PeV particles are able to get back into the Galactic disk. It will be noted that the required energy density of CR above 1 PeV can be realised and that the mechanism stands the test of energy conservation, viz. sufficient energy is injected from the Galactic Wind and from Galactic rotation to produce what is needed. (see Table 1).

There are other models proposed to accelerate CR particles up to EeV energies. Among them is the 'cannonball model' [48, 49, 50] where the sources of energy is the same SN explosions but the accelerators are not only their shock waves, but predominantly relativistic plasmoids emitted by SN into the Halo. Whether this mechanism is valid or another, such as the acceleration by multiple shocks [51], it is desirable that a substantial

contribution from the Halo be provided even at lower energies to reduce the irregularity of the CR energy spectrum compared with the case where only SNR from the Galactic Disk are contributors and there is no further accumulation outside the Disk.

Some other relevant points can now be mentioned.

(i) There is the well-known shear in the rotation of the Halo as a function of height above the Galactic Plane. The moment of inertia of gas in the Halo is of the order of 10^{62}erg ; this can be compared with a CR energy input from the Disk in 10^{10}y of $\sim 10^{58} \text{erg}$ - thus if only a small quantity of the shear energy finds its way into CR the energy gain can be large, particularly at very high energies where the particles can reach the termination shock. Here, where the magnetic field is 'wound up' or compressed by shocks, there are ideal ingredients for the acceleration of very high energy CR.

In fact the transport of CR in a rotating scattering medium has been put forward [52] as a way of 'energizing particles' but no details appear to have been given.

(ii) With a Giant Halo of the type proposed, the vast majority of CR electrons will be absorbed - the so-called EG radio background will then have a big component from the Halo.

(iii) Effects on the CMB might be expected via the Sunyaev-Zeldovich effect, similar to those detected from galaxy clusters [53].

Other sources of energy relevant to the Galactic Halo model - in addition to very rare BSNR and millisecond pulsars - are as follows:

(i) A non-negligible amount of energy has been brought into the Galaxy by way of the impact of dwarf galaxies and the energy in the associated shocks will have accelerated CR, some of which may still be trapped.

An example will suffice. A 'small' galaxy of mass $10^9 M_\odot$ colliding with velocity 400 km s^{-1} will bring in a kinetic energy of $1.6 \cdot 10^{59} \text{ erg}$. One might visualize 100 such small galaxies arriving over the life of the Galaxy, corresponding to $1.6 \cdot 10^{59} \text{ erg}$. As a datum, SN at 10^{51} erg each with a rate of 10^{-2} y^{-1} would deliver a similar amount of 'mechanical' energy. Of course, for conventional SN, where the CR energies are mainly sub-PeV, the efficiency of energy transfer to CR is probably much higher for SNR (a figure of 10% is often quoted). However, in the important post-PeV region, where sources are so difficult to find (but the total energy content is smaller) galaxy collisions might be important.

(ii) Past explosions in the Galactic Centre are similarly ‘in with a chance’. Interestingly, the energetics are rather similar. If (and it is a big ‘if’) the Galaxy has undergone Seyfert-type activity, perhaps due to the properties of the central black hole, with a lifetime $10^8 y$ and a luminosity of $10^{10} L_{\odot}$, commonly quoted, then, for 10 such explosions in the lifetime of the Galaxy, we have $6 \cdot 10^{58}$ erg released. The values are chosen so that the Galaxy would appear as a Seyfert some 10% of the time - the Universal average.

3.3.3 Halo Diffusion

Some remarks are now necessary about CR diffusion in the Halo.

Although the ‘magnetic properties’ of the Giant Halo are not known with any accuracy some rather general estimates have been made in [39] and in [20]. In the latter, the mean field B and reversal length λ were taken to be such that $B\lambda$ changes only slowly with distance from the Plane. In the Galactic Plane the mean field is $B \sim 2\mu G$ and the reversal length $\lambda \sim 0.2 kpc$; at a height of 100 kpc the corresponding mean field is $B \simeq 0.1\mu G$ and $\lambda \simeq 10 kpc$.

The fall off of field with height can be understood in terms of the expanding field-carrying SNR shells expanding out into the Halo; the same phenomena gives the increased reversal length with increasing height. The fall in plasma density with height can also be involved if, as is commonly assumed, there is a measure of equality in energy density between magnetic field and plasma energy.

It is appreciated that the above is an oversimplification because what is important for particle propagation in the Halo is the power spectrum of the irregularities - the re-entrance of a particle being influenced largely by the power contained in lengths of the order of the Larmor radius. For $\langle B\lambda \rangle \sim 0.3\mu G kpc$, taking λ as the Larmor radius, the corresponding energy - for protons - is given by $\log E = 8.5$. In view of λ being identified with the length scale having most power, the above means that there should be efficient scattering, and thus a degree of trapping, up to this energy. It can be remarked that $\log E = 8.5$ for protons is an important energy because applied to iron nuclei of the same rigidity the energy would be $\log E(Fe) \simeq 10$ i.e. the likely energy limit for Galactic iron nuclei. The spectrum denoted as ‘obs(P)’ in Figure 1 shows this is just where the measured proton spectrum begins to fall.

In the original work [38] it was pointed out that if the highest energy particles are trapped for a very long period by the termination shock, some nuclei will fragment and re-entrant protons will be mistaken for EG particles. Similarly, many apparently EG particles will be trapped Galactic heavy nuclei.

Although the energetics of the Halo acceleration model appear to be acceptable, we know neither the expected spectral shape nor the manner in which the lifetime in the Halo depends on energy. Thus, a rigorous derivation of the Halo spectrum cannot be given. Nevertheless we give below in Figures 5,6 and 7, Halo spectra which satisfy the boundary conditions.

3.3.4 Halo Trapping, without Acceleration

Following the 'General Remarks' in §3.3.1 we can examine the Halo trapping model in more detail. This alternative scenario is to postulate an emission spectrum from the Galactic Disk into a Giant Halo which has a termination shock which acts as an energy-dependent reflector but without acceleration. The emitted spectrum would have a longer 'tail' than discussed earlier and could include CR from very rare SNR in which they expand into molecular clouds and compress the magnetic fields considerably, i.e. BSNR [21] and pulsars at very early stages. (see §3.2). The essential point here is that propagation in the Galactic Disk will be so rapid that the chance of our seeing a very energetic source at any one instant is very small; the particles will be trapped in the Giant Halo, however, and, smoothed out in space and time, will contribute to the ambient CR flux at earth (see Appendix). We adopted a similar philosophy [3] to account for EG particles having come from galaxies basically similar to our own.

The lifetime inside the trapping Giant Halo can be much longer than without trapping (eg. $\sim 10^{10}$ y for PeV protons) and the expected CR intensity higher; more particularly, the energy requirements for Galactic sources can be less severe.

1. Galactic Centre explosions. If there is indeed a Giant Halo that can trap particles for very long times, then the postulated explosions in the Galactic Centre [54] the last being perhaps 10^8 years ago - can have populated the Galaxy with 'low' energy CR. Certainly, one would expect the low energy particles to be trapped for the longest period of time - and thus the spectrum to be steep. The energy release referred to earlier ($6 \cdot 10^{58}$ erg.

It must be admitted that the efficiency of conversion into cosmic rays would have to be high even if one postulates a falling CR density with distance from the Galactic Plane.

2. SNR in the Giant Molecular Ring at $R \sim 3kpc$ where the ambient ISM gas density is high may have produced many low energy CR and, again, these will be resident in the Halo. Concerning the overall energetics in the Halo the conventional sources of energy in the Disk are adequate (Table 1), provided that the Halo trapping time is essentially the age of the Galaxy.

It is necessary that the Galactic emission spectrum extends beyond the end of the 'two types of SN' of Figure 2, because of the presence of BSN. We write the Galactic emission spectrum as $I_{em}^g(E)$.

If there is trapping during the time τ which depends on energy (rigidity) as $\tau(E/Z) = \tau_0 \cdot (E/Z)^{-\delta}$ (E being the energy in GeV and τ_0 being the mean lifetime at 1GeV) then in the framework of the Giant Halo model the energy spectrum of CR accumulated during the accumulation time T is like that in a 'Giant Leaky Box':

$$I_{Halo}(E) = I_{em}^g(E) \int_0^T \frac{V_{SNR}}{V_{halo}} \nu \exp(-\frac{T-t}{Z^\delta \tau_0 E^{-\delta}}) dt \quad (2)$$

Here V_{SNR} and V_{halo} are volumes of the SNR shell and the Halo, the ratio of which in the case of spherical symmetry can be taken as the cubed ratio of radii R_{sh} and R_{halo} , where R_{sh} is the radius of the shell at the moment when CR are deconfined and begin to diffuse in the ISM, ν is the SNR explosion rate and t is the time. If there is no evolution, and all the variables under the integral do not depend on time or on coordinates inside the Halo, the integration is straightforward and gives the result:

$$I_{Halo}(E) = I_{em}^g(E) \left(\frac{R_{sh}}{R_{halo}}\right)^3 \frac{\nu Z^\delta \tau_0}{E^\delta} [1 - \exp(-\frac{TE^\delta}{Z^\delta \tau_0})] \quad (3)$$

It can be seen that at low energies the energy spectrum in the Halo follows the emission spectrum, at high energies its slope index is higher by the factor δ . The absolute intensity differs from the emitted intensity by the 'multiplication' factor which is simply νT at low energies (Figure 5a) and a 'dilution' factor of $(\frac{R_{sh}}{R_{halo}})^3$. The steepening of the spectrum occurs at the energy $E = \frac{\tau_0}{T}$ GeV.

As an example, we present in Figure 5b the energy spectrum of protons (ie the rigidity spectrum of all nuclei) in the Halo, adopting an emission spectrum $I_{em}(E) = AE^{-2.7}$

valid at all energies, $R_{sh} = 0.1\text{kpc}$ (our model value [25]), $R_{halo} = 100\text{kpc}$, $\delta = 1$ which corresponds better to ISM conditions at the Halo boundary [55], $T = 10^{10}\text{years}$ - the age of our Galaxy and $\tau_0 = 10^{17}\text{years}$. This 'lifetime' is clearly higher than the age of the Galaxy, but it simply means that low energy CR never leave the Halo and do not populate EG space. In Figure 5b we show also the so called EG energy spectrum, which is simply related to the spectrum of particles leaking from the Halo into outer space. We shall discuss it later.

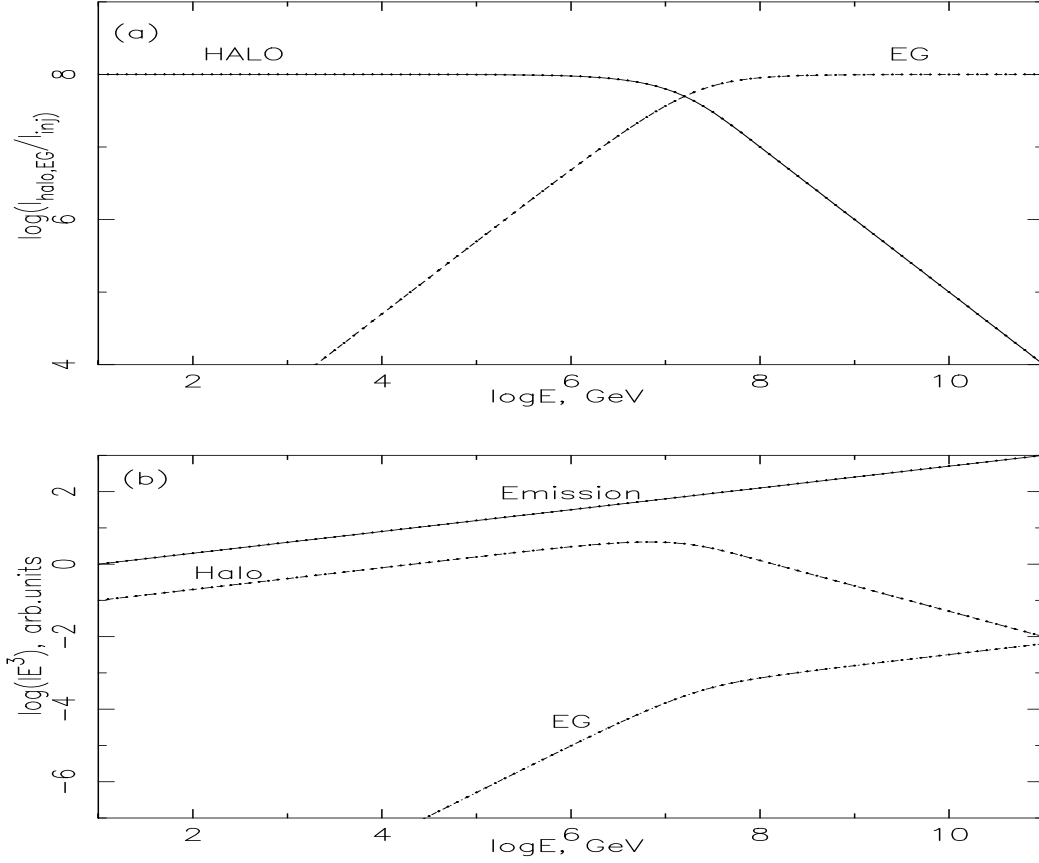


Figure 5: (a) Multiplication factor: the ratio of Halo (full line) or EG (dashed line) spectra to the emission spectrum with no spatial dilution. (b) An example of emitted Halo and EG spectra with multiplication and dilution for protons and parameters described in the text.

3.4 Extragalactic Cosmic Rays

A possible scenario is that leakage from the Halo of galaxies *similar to our own* is the source of CR populating EG space. In this case we can write the equation:

$$I_{EG}(E) = I_{em}^g(E) \int_0^T V_{SNR} \rho_g \nu [1 - \exp(-\frac{T-t}{Z^\delta \tau_0 E^{-\delta}})] dt \quad (4)$$

Here the only new notation is ρ_g which is the spatial density of galaxies in EG space. Assuming no cosmological evolution, we obtain

$$I_{EG}(E) = I_{em}^g(E) \frac{4}{3} \pi R_{sh}^3 \rho_g \nu \{T - \frac{Z^\delta \tau_0}{E^\delta} [1 - \exp(-\frac{T E^\delta}{Z^\delta \tau_0})]\} \quad (5)$$

The multiplication factor and the EG spectrum corresponding to $\rho_g = 6.4 \cdot 10^{-2} Mpc^{-3}$ [20] is shown in Figure 5. It is seen that the contribution of EG CR is small for the chosen set of parameters and cannot reduce irregularities in the spectrum caused by the stochastic nature of SN explosions. Another caveat is seen above EeV energies: the shape of the energy spectrum does not agree with the experimental observations of the 'ankle' [56].

However, if we give up the assumption that all the galaxies are identical to our Galaxy and admit that there are sufficiently numerous much more powerful galaxies in the Universe, then the possibility of agreement with experiment appears. The additional assumption that CR emitted into the Halo have a mixed mass composition improves this agreement. Figure 6 shows the Emission, Halo, EG and total spectra for the 4-component mass composition close to that indicated in [57] for 1 TeV per nucleus: 0.487-P, 0.310-He, 0.121-O and 0.082-Fe and for the 10-fold reduction of the mean distance between EG sources. It is seen that all the main features of the all particle spectrum in the PeV-EeV region and above are fairly well reproduced.

4 Discussion

4.1 The preferred model

We mentioned earlier that in our Single Source Model of the knee we introduced the so called 'background' spectrum, which we attributed to the contribution from many old and distant SN [9]. We now go further and assume that this contribution is integrated in

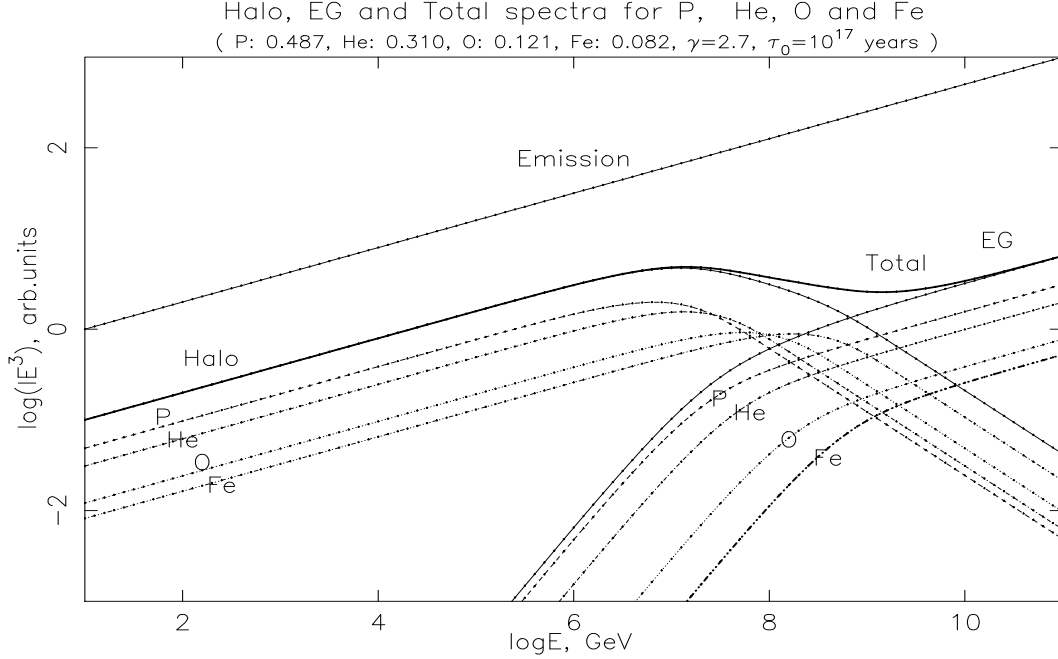


Figure 6: Emission, Halo, EG and total spectra for the 4-component mass composition: 0.487-P, 0.310-He, 0.121-O, 0.082-Fe. The EG mass composition at high energies is the same as that in the Halo at low energy in this model. In practice the EG composition and spectrum will be modified by propagation effects.

space and time within the Giant Halo and associate this background with the model of the Halo + EG spectrum described above. Figure 7a shows all four major components of the model: SNR of the Disk, Halo, EG and SS. CR energy spectra from SNR were made from standard rigidity spectra (Figure 1a) adopting the mixed composition [57] at 1 TeV/nucleus. The total Halo + EG spectrum of our model has been normalized to our phenomenological background at 1 EeV. Figure 7b shows the sum of all four components as the total spectrum with its irregularity. It is seen that, due to smoothing effect of the Halo, irregularities below the knee are reduced to the level observed in the experiment; the standard deviation for $\log E = 2.5 - 4.5$ is $\Upsilon = 0.07$ to be compared with the experimental value of $\lesssim 0.05$ (see §3.3.2 and the Appendix).

The composition of the CR energy spectrum in our model is similar to that in the so called 'three sites model' of Biermann [57]. The difference is that we introduce a Giant Halo with extended trapping as the smoothing mechanism, which makes the spectrum looking as a nearly regular power law.

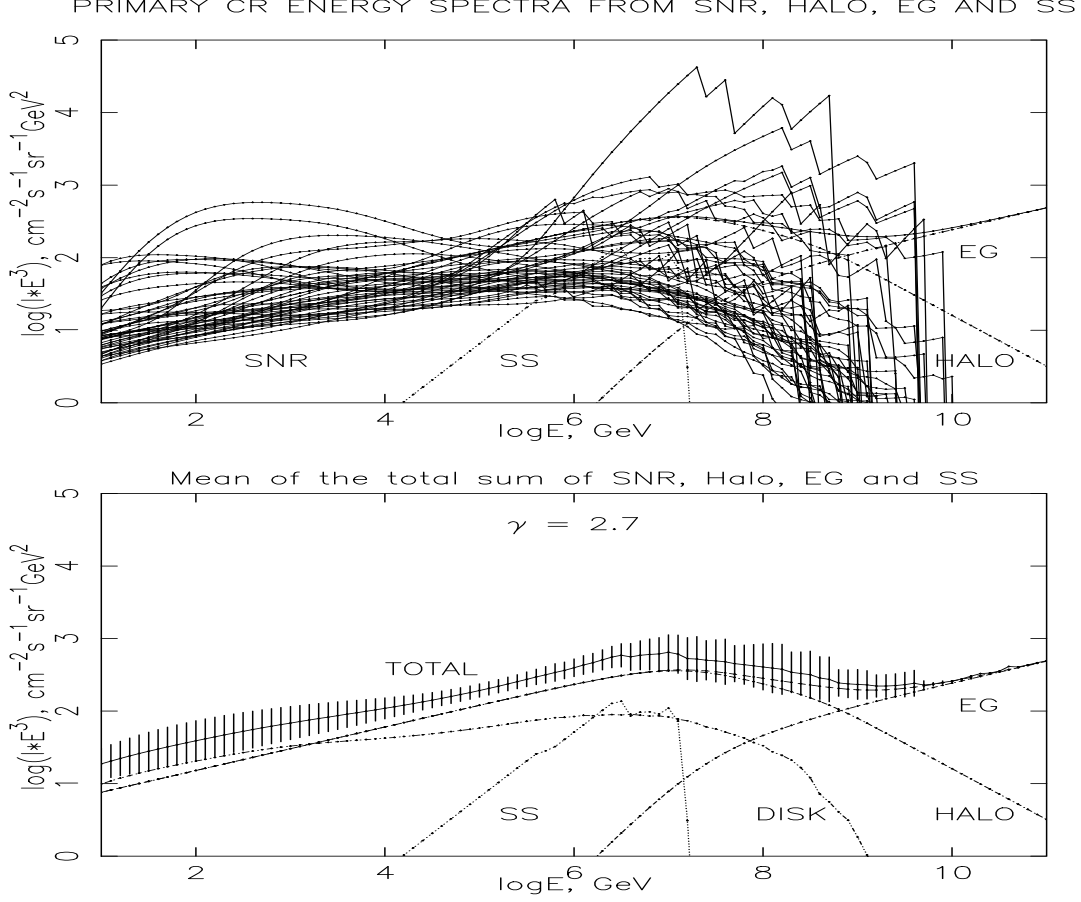


Figure 7: (a) Four major components of the CR spectrum: SNR in the Galactic Disk, Halo, EG and SS. (b) The all particle CR spectrum as the sum of four components, shown in (a). The irregularity of the spectrum is substantially reduced due to the smoothing effect of the Halo. The slope index of the emission spectrum in the Halo is $\gamma = 2.7$.

We should like to underline the expense by which we achieved the general agreement between our model and the experiment. It is:

- (i) Introduction of a hypothetical Giant Halo as an intermediate structure between the Galactic Disk and EG space.
- (ii) Assumptions about the Galactic Wind which creates the Termination Shock at the boundary of the Giant Halo. The leakage from this boundary makes the Halo similar to the Giant Leaky Box.
- (iii) The emission spectrum of CR in the Halo has a power law shape with slope index $\gamma = 2.7$ in the entire energy range from GeV to hundreds of EeV. This value of γ is essentially ad hoc but there are, perhaps, ways of generating it, for example, explosions

at the Galactic Centre, or the collisions of small galaxies.

(iv) EG CR appear as the result of the leakage from halos of all galaxies and some of them should be much more powerful than our Galaxy.

There are attractive consequences of this model which agree with the observations (consequences which were not put in at the start):

- (i) the mass composition beyond the knee becomes heavier than below;
- (ii) the EG CR also have a mixed mass composition with a predominance of protons, because they escape from halos first (propagation effects in EG space may reverse this result, however [58]);
- (iii) the problem of the small radial gradient of CR is reduced due to the big contribution of the Halo with its much more uniform spatial distribution of CR than in the Disk;
- (iv) the CR isotropy is explained by the same uniform spatial distribution in the Halo.

As for the model with no Halo, where the transition from Galactic to EG CR occurs immediately after the termination of the former at $E_{max} \approx 0.04 - 0.1 EeV$ (Figures 1, 2) and at lower energies only SNR contribute with no substantial EG fraction [14, 15], then the problem of the big irregularity of the spectra expected in this model remains unsolved. In this paper we do not examine the problems of the ultrahigh energy, tens of EeV EG particles and their interaction with the cosmic microwave background, nor the possibility that there are no truly extragalactic particles but simply very energetic nuclei trapped in the Giant Halo [38].

Certainly, our model raises more questions than it gives answers. At the present time it is purely phenomenological and some of its problems are:

(i) We are not sure which of the mechanisms give the particles above E_{max} for SNR. It can be young supernovae (BSNR), young pulsars, cannonballs, re-acceleration in the Halo or others. At the moment we prefer the re-acceleration mechanism because it seems to be more regular than the others and works continuously, unlike pulsars or SNR.

(ii) We do not know why the so called emission spectrum in the Halo needed to fit the experimental data, should have $\gamma = 2.7$, which is coincident with the spectrum in the Galactic Disk but does not coincide with the slope of injection spectrum from our SN, which has the slope $\gamma = 2.15$; our suggestions of Galactic Centre explosions and galaxy collisions, although reasonable, have no possibility of proof.

(iii) It should be remarked that the Galactic Wind will affect propagation of low energy particles generated in Disk sources and propagating therein. No allowance has been made for this effect.

(iv) The contribution of the Halo at GeV energies has to be reduced compared with that expected from the spectrum with $\gamma = 2.7$, at least at distances more than 50 kpc from our Galaxy, in order not to conflict with the low flux of $> 0.1\text{GeV}$ gamma-rays from Large and Small Magellanic Clouds [59]; the clouds are inside the Halo according to parameters adopted in the present model. It can be remarked, however, that in the work on acceleration in the Giant Halo [39] there is a radial gradient which reduces the intensity at the Magellanic Clouds sufficiently.

We hope to clarify some of these problems in subsequent papers.

4.2 The conventional - but not preferred - situation

In view of the fact that, conventionally, we expect the spectrum of particles escaping from the Disk to have an index $\gamma = 2.15$, we have made calculations also for this situation, for the sake of completeness.

In Figure 8 we show the all particle spectrum as the sum of the four components: DISK, HALO, EG and SS similar to that shown in Figure 7b, but for the case of the emission spectrum in the Halo, having slope index $\gamma = 2.15$. The EG contribution is increased by a factor of 8. The contribution of the Halo to the total CR intensity at energies below 10^4GeV is negligible and the irregularity of the spectrum is rather large (that is why we prefer the steeper emission spectrum with $\gamma = 2.7$). Specifically, for the range $\log E = 2.5 - 4.5$ the standard deviation of the sagitta is $\sigma \sim 0.16$, whereas we find, experimentally, a sagitta $\lesssim 0.1$. However, there are complications (see Appendix).

5 Conclusion

Although the problem of the origin of particles with energy in PeV-EeV region can hardly be said to be solved, there appear to be two ways of injecting CR beyond the knee and up to a rigidity of $\log E = 8.5$ into the 'CR pool': very energetic SNR or young pulsars with subsequent trapping in a Giant Halo (size of $\sim 100\text{kpc}$) with, or without subsequent acceleration. A 'long shot' is the dominance of a small number of sources such as the pulsar

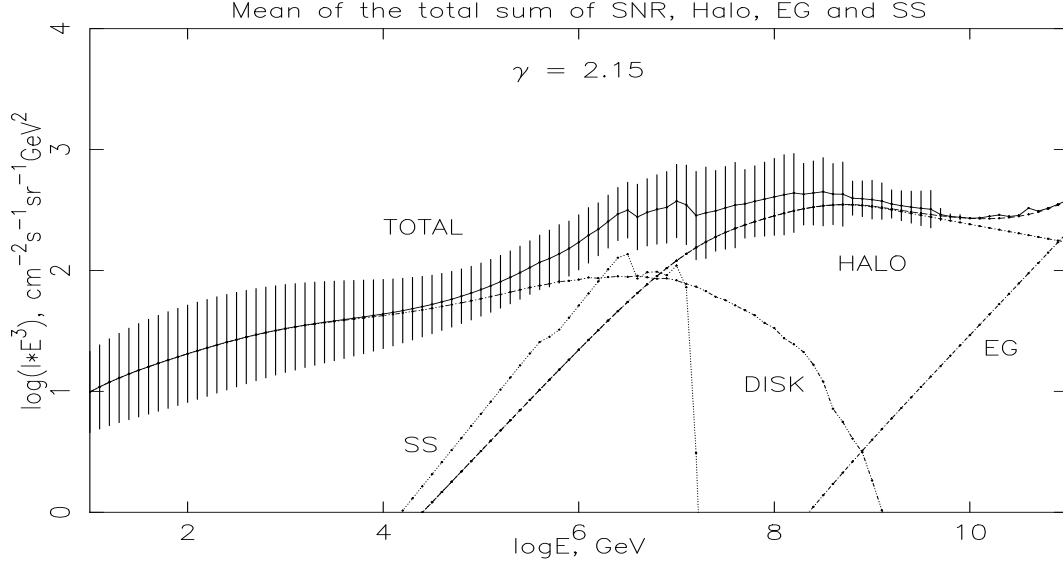


Figure 8: The all particle CR spectrum as the sum of four components, similar to that shown in Figure 7b, but for the emission spectrum in the Halo, having slope index $\gamma = 2.15$. The irregularity of the total spectrum is substantially higher than for $\gamma = 2.7$.

B0656+14 inside the Monogem Ring SNR which by chance give few irregularities caused by the stochastic nature of multiple sources. However, as for pulsar B0656+14, extended trapping of particles above PeV energies inside the Monogem Ring shell is needed.

We should like to stress that, independently of their actual origin, *CR particles above PeV energies most likely come predominantly from the Galactic Halo with extended trapping*. It is assumed that the Galactic Wind and its termination shock provide conditions for such trapping. The small irregularity of the observed CR energy spectrum, as well as the lack of large anisotropies in arrival directions and the small radial gradient of CR, means that *the contribution of the Giant Halo to the total CR intensity is substantial at all energies up to about 10^{10} GeV* . The leakage from the Halo of our and other galaxies is the source of EG CR, with some of these galaxies (*eg* AGN) being much more powerful sources of CR than our Galaxy.

Acknowledgments

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Appendix

The relevance of variations of spectral shape

It is apparent that the fluctuations in spectral shape predicted above the knee for at least some of the models considered are dramatic and this provides the main case for postulating a Galactic Halo with, or without, acceleration. At lower energies - where direct measurements of individual nuclear charges have been made - there are also significant fluctuations in shape predicted in going from one 'run' (a particular, randomly chosen set of SN distances and ages) to another. We examine this aspect in some detail, starting with the results, and 'predictions', for 'heavy' nuclei. An energy range $3 \cdot 10^{10}\text{eV}$ to $3 \cdot 10^{12}\text{eV}$ has been chosen over which to study the spectral shapes insofar as direct measurements have been made in this range. The choice of \pm one decade in energy over which to search for variations of spectral shape comes from two factors:

(i) Inspection of our predicted spectra (e.g. Figures 1 and 2 shows that 'curvature' is often present on scales of the order of a decade).

(ii) Experimental measurements are subject to both random and systematic errors. We consider that the random errors indicate that wide bins of energy should be taken. We consider that systematic errors will usually cause slowly varying changes in intensity which will only rarely contribute spurious curvature in the spectrum.

As a first approach we determine the sagitta, δ , of the difference between the intensity at $3 \cdot 10^{11}\text{eV}$ and that found by linear (in the logarithm) interpolation between the limiting energies ($3 \cdot 10^{10}\text{eV}$ and $3 \cdot 10^{12}\text{eV}$).

Two aspects are studied:

(i) The evidence for curvature in the spectrum, i.e. a finite value of δ ; the basic shock acceleration model adopted by us [60] shows increasing negative curvature as the time of acceleration proceeds and observation of the correct curvature would give confidence in the model.

(ii) The likelihood, or otherwise, of each model providing an acceptable fit to the data in the sense of not producing too high a value of δ .

We start with the experimental evidence for $Z \geq 2$; the results are shown in Figure A1. The sources of the data are given in the caption to the Figure. It is evident that there is a measure of consistency between the different elements and that $\langle \delta \rangle$ is negative.

Specifically, the mean is $\langle \delta \rangle_{obs} = -0.11 \pm 0.03$. It will be noted that there are 3 observations (out of 13) further than one sigma from the mean, in comparison with an expected number of 4.

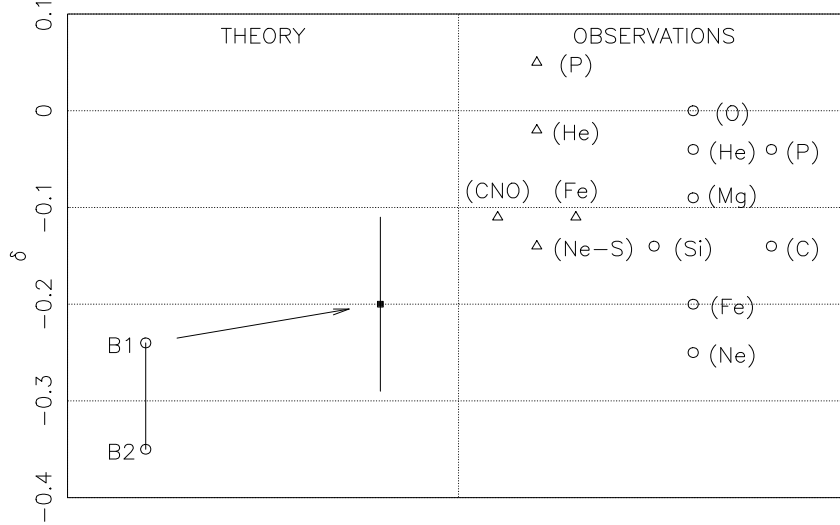


Figure A1: Sagittas (δ - the spectral shape factor) for the range $3 \cdot 10^{10} - 3 \cdot 10^{12}$ eV/nucleon. Key: 'THEORY'. Shock acceleration model [60]. B1: 'efficiency', $\eta = 10^{-2}$; B2: $\eta = 10^{-4}$. The value arrowed is after allowance for SNR of different properties and environments. 'OBSERVATIONS'. Δ - [61], \circ - [62]. The uncertainties on the points are, typically ± 0.1 .

Turning to expectation, the shock acceleration model predicts a spectral shape at our adopted time of SNR particle release ($8 \cdot 10^4$ y) which depends on the parameters of the SNR and ISM. Results for two values of the injection efficiency ($\eta = 10^{-4}$ and $\eta = 10^{-2}$) are given in the Figure. Unlike the situation at higher energies, where there is a dramatic upturn (in the $E^2 I(E)$ plot), the sagittas here are quite small.

Allowance for the frequency distribution of all the SNR and ISM properties is necessary and an approximate estimate has been made; surprisingly, perhaps, the reduction of δ is rather small. This is in contrast to the situation near the maximum energy where the smoothing introduced is much more marked and the observed knee cannot be reproduced with many different SNR. It is at the knee energy (3 PeV) where a 'Single Source' is needed. At the energies concerned in this section ($3 \cdot 10^{10} - 3 \cdot 10^{12}$ eV) we are dealing with the 'background' spectrum derived from many SNR.

We note that the observed sagitta, with mean -0.11 ± 0.05 , is not inconsistent with the expected shock model prediction: -0.1 to -0.3, although the range of predictions is, admittedly, wide. What can be said, however, is that there is support for 'heavy' nuclei, at least, being accelerated by the shock process insofar as curvature seems to be a property of the mechanism.

Turning to comparison with our model predictions given in the present work, this is not straightforward in the sense that a simple $E^{-2.15}$ (or $E^{-2.7}$) injection spectrum was adopted, i.e. the mean δ is equal to zero. Thus, we need to make a systematic shift to the mean of the derived sagittas for the constituent spectra. What is important is the spread in sagittas from run to run. Figure A2 shows the frequency distribution for a series of situations, as indicated in the caption. As remarked already, systematic displacement

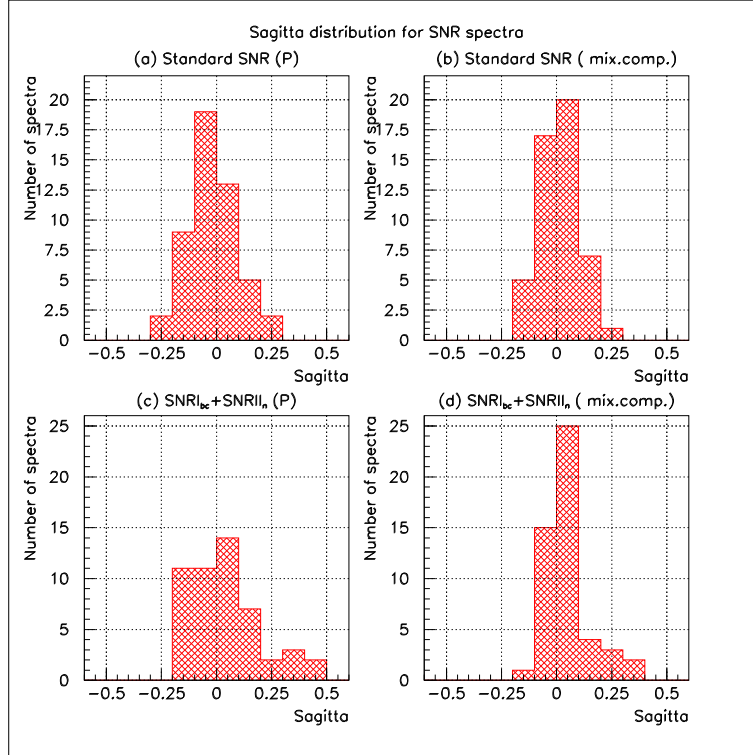


Figure A2: Distribution of sagittas of the energy spectra for the range $3 \cdot 10^{10} - 3 \cdot 10^{12}$ eV/nucleon: (a) standard SNR, protons, $\langle \delta \rangle = -0.018, rms = 0.112$; (b) standard SNR, mixed composition, $\langle \delta \rangle = 0.014, rms = 0.091$; (c) $SNRI_{bc}+SNRII_n$, protons; $\langle \delta \rangle = 0.04, rms = 0.16$; (d) $SNRI_{bc}+SNRII_n$, mixed composition, $\langle \delta \rangle = 0.048, rms = 0.103$.

is necessary to allow for a concave injection spectrum. The result is summarized in

Figure A1, where it will be noted that the situation with the model in which there are 'super-SNR' and no Halo gives a spread about twice that 'expected' : $\sigma = 0.16$ compared with our observed 0.1 ± 0.03 , a 2-sigma effect. With a Giant Halo, however, and with a Galactic emission spectrum having $\gamma = 2.7$ (Figure 7) the situation is more agreeable ($\sigma = 0.07$ compared with 0.1). Before making a final conclusion with respect to the sagitta method, some discussion for protons is necessary. Here, for $E : 3 \cdot 10^{10} - 3 \cdot 10^{12} \text{eV}$, we have $\langle \delta \rangle = 0.0 \pm 0.05$ (from 2 observations) , viz., smaller than for the heavier nuclei. Insofar as the measurements for protons extend to higher energies than for the heavier particles, we can determine δ over a larger energy range. The result is, for the range $10^{11} - 10^{14} \text{eV}$: $\delta_P = +0.10 \pm 0.06$ Such a result is surprising, in that for this enhanced energy range the value should be larger (negative) than for the lower energy range if shock acceleration is valid. Two possibilities spring to mind:

- * the measurements are imprecise;
- * the protons are drawn preferentially from regions of the ISM where the temperature is low, the acceleration efficiency is low and the spectrum more nearly straight.

The second possibility seems the more likely.

The situation with the sagittas is therefore rather confused: observationally, for nuclei with $Z \geq 2$ we have $\delta = -0.11 \pm 0.03$ and for protons, $\delta = 0.0 \pm 0.05$, both for $\log E = 2.5 - 4.5$. Theoretically, for shock acceleration we expect $\delta \sim -0.2 \pm 0.1$. Thus, it looks as though a contribution of ~ 0.1 is required from stochastic processes. Such a contribution could come from either $\gamma = 2.15$ or 2.7 although $\gamma = 2.7$ is preferred.

Moving to higher energies still, without a Giant Halo, the fluctuations increase rather quickly with energy (*eg* Figures 1 and 2) and rapidly become too large. An estimate of the observed sagitta for $\log E : 8 - 11$ is $\delta = -0.2 \pm 0.1$. Extrapolation of the results of Figure 2d, corresponding to an inclusion of BSNR, leads to a σ -value of $\simeq 1.6$, i.e. very much larger than observed. Indeed the negative value of δ seen is usually associated with the 'ankle', above which extragalactic particles rapidly dominate. This is particularly true above the knee when rare, ultra-energetic, SNR or pulsars are invoked to endeavour to explain the intensity. A Giant Halo appears to be necessary to smooth the spectra. If we invoke acceleration at the termination of the shock (at $R \sim 100 \text{kpc}$) as the source of the 'Halo' particles (*eg* Figure 5) then their flux - which will have less variability - will

also dilute the resulting spectral fluctuations considerably.

The final magnitude of the fluctuations expected for the Halo component is not easy to calculate, but an estimate can be made. A number of factors are important, including variability in the local Galactic Wind which reduces the intensity of the lower energy particles ($E \leq 1\text{PeV}$) which are endeavouring to re-enter the Galaxy, and, at all energies, the fluctuating, wave-like nature of the shocks [39]. The last mentioned have an amplitude in velocity of $\sim \pm 12\%$ at the boundary; insofar as the energy carried, and thus transferred to CR, goes as the square of the velocity, there is a 24% temporal variability. The original source of the energy, the Galactic Wind, is variable not only in time but also in space, being greater above the spiral arms than in the inter-arm regions. Galactic trapping will smooth the ensuing fluctuations to a large extent and it seems unlikely that there will be sagittas, measured over two orders of magnitude for the range $\log E$: 6 - 9, of more than about 10%, i.e. $\log \delta = 0.04$. As Figure 4 indicates, this is allowable.

Table 1. **Factors relevant to a Galactic Halo** [39]

Emission from the Galactic Disk	Luminosity ($erg \cdot s^{-1}$)	
Cosmic Rays from the 'usual' SNR (10^{50} erg per SNR, rate $100^{-1}y^{-1}$)	$3 \cdot 10^{40}$	
Starlight (10^{10} stars, each of $1 L_{\odot}$)	$4 \cdot 10^{43}$	
Galactic Wind ($1M_{\odot}y^{-1}$ with velocity $300kms^{-1}$)	$3 \cdot 10^{40}$	
Galactic Halo		
(radius 100 kpc, energy independent lifetime 10^8y (or $10^{10}y$)		
1. No Acceleration	Energy density ($eVcm^{-3}$)	
Energy density of CR escaping from the Disk	$1.5 \cdot 10^{-3}$	(0.15)
Energy density in the wind	$1.4 \cdot 10^{-2}$	(1.4)
Energy density in the rotating wind	$2.5 \cdot 10^{-3}$	(0.25)
2. Acceleration at the Termination Shock		
Energy density of CR (and gas and field, all approximately equal), each:		
Mean over 100 kpc	$1.5 \cdot 10^{-2}$	(1.5)
Value at 100 kpc	$6 \cdot 10^{-4}$	($6 \cdot 10^{-2}$)

Energy density of CR above 1 PeV, pervading the Halo	10^{-4}	(10^{-2})
(Energy density needed to fit observations of the CR spectrum)	10^{-4}	(10^{-2})

References

- [1] Hillas A.M. 1984, *Ann. Rev. Astron. Astroph.*, **22**, 425
- [2] Haungs A. et al. *Rep. Progr. Phys.*, 2003, **66**, 1145
- [3] Erlykin A.D. and Wolfendale A.W. 1999, *Europ. J. Phys.*, **20**, 409
- [4] Erlykin A.D. and Wolfendale A.W. 2000, *Astron. Astroph.*, **356**, L63
- [5] Erlykin A.D. and Wolfendale A.W. 2001, *J. Phys. G: Nucl. Part. Phys.*, **27**, 941
- [6] Erlykin A.D. and Wolfendale A.W. 2003, *J. Phys. G: Nucl. Part. Phys.*, **29**, 709
- [7] Ostrowski M. 2001, *Proc. 27th Int. Cosm. Ray Conf., Hamburg, Inv., Rapp. and High. Papers*, 162.
- [8] Thorsett S.E. et al. 2003, *Astroph. J. Lett.* **592**, L71
- [9] Erlykin A.D. and Wolfendale A.W. 1997, *J. Phys. G: Nucl. Part. Phys.*, **23**, 979
- [10] Hörandel J.R., 2003, *Astropart. Phys.*, **19**, 193
- [11] Kampert K.H. et al., 2004, *Nucl. Phys. B (Proc. Suppl.)*, **136**, 273
- [12] Erlykin A.D. and Wolfendale A.W. 2005, *Astropart. Phys.*, **23**, 1
- [13] Haungs A. et al. 2003, *28th Int. Cosm. Ray Conf., Tsukuba*, **2**, 985
- [14] Berezhinsky V.S. et al., 2004, *Astropart. Phys.*, **21**, 617
- [15] Berezhinsky V.S. et al., 2005, *Phys. Lett. B*, **612**, 147
- [16] Wibig T. and Wolfendale A.W., 2005, *J. Phys. G: Nucl. Part. Phys.* **31**, 255
- [17] Biermann P.L., 1993, *23d Int. Cosm. Ray Conf., Calgary, Inv., Rapp. and High. Papers*, 45
- [18] Sveshnikova L.G., 2003, *Astron. Astroph.* **409**, 799

- [19] Erlykin A.D., 2004, Invited talk at 19th ECRS, Florence, Italy, 30.08-4.09.04, to be published in Int. J. Mod. Phys., 2005
- [20] Erlykin, A.D., Wibig T. and Wolfendale, A W, 2001, New J. Physics, **3**, 18.1
- [21] Bell A.R., 2004, Mon. Not. Roy. Astr. Soc., **353**, 550
- [22] Erlykin A.D. and Wolfendale A.W., 2004, Astropart. Phys., **22/1**, 47
- [23] Erlykin A.D. and Wolfendale A.W., 2001, Proc. of 36th Rencontres de Moriond, 'Very High Energy Phenomena in the Universe', Les Arcs 1800, 177
- [24] Giller M. and Lipsky M., 2001, 27th Int. Cosm. Ray Conf., Hamburg, **6**, 2092
- [25] Erlykin A.D. and Wolfendale A.W., 1998, Astropart. Phys. **8**, 265
- [26] Tonwar S. et al., 2004, 19th ECRS, Florence, Italy, to be published in the Int. J. Mod. Phys., 2005
- [27] Fomin Yu.A. et al., 2003, Proc. 28th Int. Cosm. Ray Conf., Tsukuba, **1**, 119
- [28] Bednarek W. and Bartosik M., 2004, Astron. Astrophys., **423**, 405; astro-ph/0405310
- [29] Lagutin A.A. et al., 2001, Proc. 27th Int. Cosm. Ray Conf., Hamburg, **5**, 1900
- [30] Erlykin A.D. et al., 2003, Astropart. Phys., **19**, 351
- [31] Aharonian F. et al. 2005, Astron. Astrophys. **432**, L25
- [32] Blasi P. and Vietri M., 2005, astro-ph/0503220
- [33] Wdowczyk J. and Wolfendale A.W., 1984, J. Phys. G, **10**, 1599
- [34] Clay R., 1998, Proc. Astr. Soc. Austr., **15**, 208
- [35] Kulikov G.V. and Zotov M.Yu., 2004, Izv. RAN, ser.fiz., **68**, 1602 (in Russian); astro-ph/0407138
- [36] Benko G. et al., 2004, Izv. RAN, ser.fiz., **68**, 1599 (in Russian); astro-ph/0502065

- [37] Ginzburg V.L. and Syrovatskii S.I., 1964, The Origin of Cosmic Rays, Pergamon Press
- [38] Wdowczyk J. and Wolfendale A.W., 1995, 24th Int. Cosm. Ray Conf., Rome, **3**, 360
- [39] Völk H.J. and Zirakashvili V.N., 2004, Astron. Astrophys., **417**, 807
- [40] Moore B. and Davis M., 1994, Mon. Not. Roy. Astr. Soc., **207**, 209
- [41] Zirakashvili V.N. et al., 1996, Astron and Astrophys., **311**, 113
- [42] Suto Y. et al., 1996, Astrophys. J., **461**, L33
- [43] Veilleux S. et al. 2005, astro-ph/0504435
- [44] Jokipii J.R. and Morfill G., 1985, Astrophys. J., **290**, L1
- [45] Jokipii J.R. and Morfill G., 1987, Astrophys. J., **312**, 170
- [46] Stone E.C. 2003, 28th Int. Cosm. Ray Conf., Tsukuba, **8**, 383
- [47] Breitschwerdt D. et al., 2002, Astron. Astrophys., **385**, 216
- [48] Plaga R., 2002, New Astronomy, **7**, 317
- [49] Dar A., 2004, astro-ph/0408310
- [50] De Rujula A., 2004, 19th ECRS, Florence, Italy, to be published in Int. J. Mod. Phys., 2005; astro-ph/0411763, astro-ph/0412094
- [51] Bykov A.M. and Topygin I.N., 1997, 25th Int. Cosm. Ray Conf., Durban, **4**, 365
- [52] Webb G.M. and Jokipii J.R. 1990, 21st Int. Cosm. Ray Conf., Adelaide, **4**, 122
- [53] Myers A.D. et al., 2003, Mon. Not. Roy. Astr. Soc., 2004, **347**, L67
- [54] Said S.S. et al., 1982, J. Phys. G: Nucl. Part. Phys., **8**, 383
- [55] Erlykin A.D. and Wolfendale A.W., 2002, J. Phys. G: Nucl. Part. Phys., **28**, 2329
- [56] Nagano M. and Watson A.A., 2000, Rev. Mod. Phys., **72**, 689

- [57] Biermann P.L. and Wiebel-Sooth B., 1999, Astronomy and Astrophysics - Interstellar Matter, Galaxy, Universe, Landolt-Börnstein, **3**, 37
- [58] Wibig T. and Wolfendale A.W., 2001, 27th Int. Cosm. Ray Conf., Hamburg, **5**, 1987
- [59] Chi X. and Wolfendale A.W., 1993, J. Phys. G: Nucl. Part. Phys., **19**, 795
- [60] Berezhko E.G. et al., 1996, J. Exp. Theor. Phys., **82**, 1
- [61] Zatsepin V.I. and Sokolskaya N.V., 1999, 26th Int. Cosm. Ray Conf., Salt Lake City, **4**, 136
- [62] Zatsepin V.I. et al., 2004, Izv. RAN, ser. fiz., **68**, 1593